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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

EFFECTS OF PAVEMENT ROUGHNESS ON NAVAL AIR OPERATIONS

by John M. Ferritto and James B. Forrest, Ph D

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A review of the problem of airfield roughness has been made. Either as a result of bad construction methods or, more generally, gradual deterioration, variations that impair the performance of aircraft during ground operations may occur in pavement surface elevations. Although no general standards for evaluating roughness have been accepted, use of the level of 0.4 g maximum peak vertical acceleration response of aircraft in ground CONT

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INTRODUCTION

Either as a result of bad construction methods or, more generally, gradual deterioration, variations may occur in pavement surface elevations that impair the performance of aircraft during ground operations. These variations in surface elevation over the length of the pavement result in what is termed "airfield roughness." The severity of this problem may be expected to grow worse with increasing gross weights of aircraft and higher ground speeds. Greater aircraft masses and higher speeds can magnify the effects of long-wavelength pavement irregularities that were formerly of little consequence. The United States Navy, including the Marine Corps, operates more than 80 airfields in support of its air mission. In accordance with this responsibility the Naval Facilities Engineering Command sponsored this investigation to evaluate: (1) the effects of runway roughness on the operations of Naval aircraft and (2) the utility of incorporating roughness assessments into the Navy's procedures for airfield pavement evaluation.

With the interaction between the aircraft and the pavement, roughness also induces increased stresses in pavements and may create nonuniform elastic settlements. Consideration of the increased stresses in pavements can be an important aspect of roughness [1]; however, this consideration is outside the scope of this report.

The effects of pavement roughness on the operational safety of airplanes include structural overload, fatigue damage, interference with instrument readability, decrease in ground control, and general discomfort of crew and passengers. Because of difficulties involved in acquiring sufficient recorded data on the structural or avionic requirements most researchers have concentrated upon tying roughness to the human tolerance factor.

Aircraft manufacturers have not developed either satisfactory instrumentation or indexes to measure pavement roughness. There is no accepted method or equipment used for routinely measuring pavement roughness or waviness. Suitable roughness standards have not been established for construction of the pavement, nor for maintenance over the life of the pavement; this is not a factor in airport certification. Direct maintenance cost of very expensive aircraft is increasing. The Boeing Company analyzed aircraft maintenance costs [2] and found that maintenance of the landing gear system of a Boeing 707 represents more than 37% direct maintenance cost of the aircraft. This is the largest cost for a single system and can be compared to only 21% for maintenance of the total power plant system.

Typical roughness induces vertical accelerations in the airplane that are partly absorbed by the landing gear and flexural capability of the wings and airframe and partly transmitted to the cockpit, the cargo or passenger areas, etc. Thus, roughness and waviness are shown to be detrimental to airframe structural integrity and metal useful life. High vertical accelerations, when transmitted to the cockpit, impose physical stresses upon the pilots, inhibiting aircraft control and instrument monitoring. To summarize, measuring of runway roughness is desirable: (1) to insure safety of and comfort in the aircraft; (2) to provide an objective method of evaluating the performance of pavements; (3) to provide a basis for economical maintenance and upgrading of existing runways; and (4) to provide adequate specifications for defining the useful life of new pavements.

DEFINITION OF ROUGHNESS

Current Roughness Standards

Criteria for defining allowable airfield roughness levels generally fall into three major categories: (1) quality of ride, or subjective evaluation; (2) physical height of bumps or irregularities; and (3) vertical accelerations experienced at various locations within the aircraft.

Quality of Ride. The quality of ride can be evaluated by compiling the observations of pilots and passengers or by recording pilot or passenger complaints. In one method used in highway evaluation, subjective ratings of pavements are obtained by having a group of experienced raters ride over the pavement section and record their opinions as to its rideability [3]. This method provides what is termed the Present Serviceability Rating and may be applicable to highways where relatively similar vehicles traverse sections of highway within a relatively narrow velocity range. However, it could be inefficient for diverse types of aircraft performing a variety of ground operations on a pavement section. A procedure based upon pilots' complaints, however, appears to be the prevalent means of roughness evaluation currently used by the Navy.

Physical Height of Irregularities. Methods of defining roughness in terms of physical height of irregularities have long been used in providing construction standards. Typical construction standards for new runways limit pavement irregularities to less than 1/8-inch (3.17 mm) elevation change per 10 feet (3.04 m) in length, measured parallel to or perpendicular to the centerline. In Reference 4 it is suggested that vertical deviations be kept to less than 0.05 foot (1.27 mm) in 100 feet (30.4 m). Houbolt [5] presents a criterion calling for less than 0.08 foot (2.03 mm) elevation difference in 250 feet (76.2 m). For maintenance purposes, tolerable surface deviations from a straight edge of length ℓ are to be less than $0.005\sqrt{\ell}$. Different analytical treatments have been used to quantify physical height irregularities, such as the power spectral approach [5]. This approach, based upon limiting the accumulation of bump heights at specific wavelengths, is discussed later in more detail.

In general, newly constructed runways have been satisfactory; however, deterioration develops with age and usage. This deterioration takes many forms and may result from: (1) settling of the base course and subgrade, (2) daily and seasonal environmental changes to the subgrade under usage, (3) surface irregularities induced by excessive loadings, and (4) unevenness introduced by auxiliary construction of drainage systems and lighting.

Vertical Acceleration Levels. Most recent approaches to defining roughness criteria have concentrated upon maximum tolerable vertical acceleration levels. Surveys of pilots [6] suggest that vertical accelerations exceeding 1/3 g are unacceptable and that 1/2-g levels seriously affect pilot performance. However, no distinct line exists between permissible and intolerable levels. Reference 7 notes that acceptable levels vary with type of aircraft and required procedures and maneuvers. Houbolt [5] suggests vertical accelerations be less than 0.3 g. Figure 1 gives criteria on human tolerance to vibration [8]. As noted over a range of frequencies, the tolerance level is fairly constant. A value of 0.4 g has been used to identify acceptable limits on military aircraft; this is in general agreement with other findings [9].

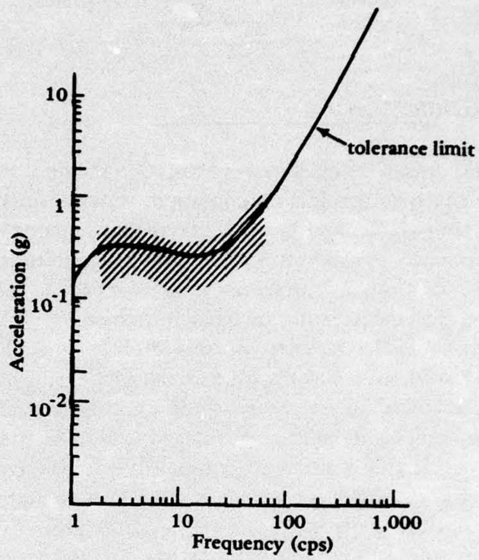

Figure 1. Human tolerance vibration criteria [8].

Pavement Roughness Considerations in Naval Aircraft Design

Strength requirements for design of Naval aircraft are defined in Reference 10. Criteria for aircraft design based on pavement roughness are given in

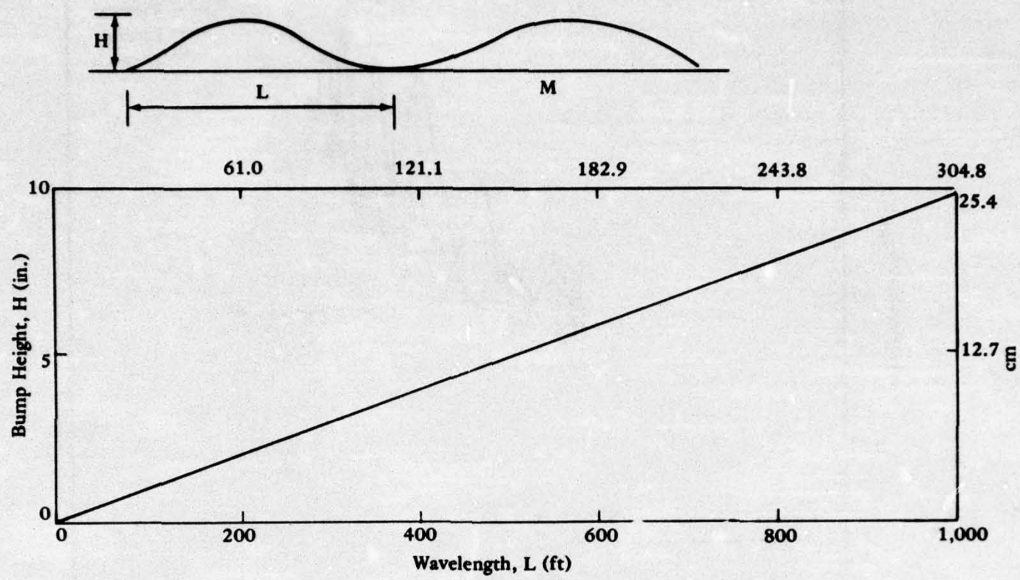

Figure 2. Bump height versus wavelength design criteria for Naval aircraft [10].

Figure 2. Requirements for both takeoff and landing of aircraft are specified in terms of (1 - cosine) undulations of constant wavelength. Figure 2 specifies all the combinations of undulation heights and lengths that must be included. During takeoff the aircraft must be capable of accelerations using maximum power to takeoff speed over all critical combinations of specified bump heights and wavelengths. In addition, the landing-gear wheels must be able to run over single (1 - cosine) contours with a minimum length of 2 feet (0.6 m) and a maximum length equal to the horizontal distance traveled during the compression stroke of the landing-gear shock struts and tires.

Requirements covering aircraft personnel needs are considered to be satisfied with respect to roughness if the structure of the aircraft is not exposed to accelerations or vibrations that may impose structural damage [11]. In the case of carrier-based aircraft (with their design loads of 10 g), structural design for roughness-generated loadings is not the controlling factor. Also, in many cases flight loads produce stresses that exceed landing or taxiing stresses on the wings. NASA has collected structural requirements specifying acceleration tolerances for a number of aircraft. Figures 3 and 4 give requirements for a C-130 turboprop-driven aircraft and a KC-135 jet-propelled aircraft, respectively.

MEASURING TECHNIQUES

Direct Aircraft Instrumentation

Numerous experiments have been conducted in which aircraft have been instrumented with accelerometers and time histories of motion recorded (see References 4, 7, 12, 13). These tests, limited to specific circumstances without a general correlation to roughness, can be used to locate bad areas as they relate to the specific conditions such as test-aircraft weight, tire pressure, and landing gear pressure.

Park [14] used an instrumented standard truck to measure highway roughness. Absorbed power, defined as the energy flow rate, is dependent on the anatomical properties of the human body and is related to subjective responses by passengers. The absorbed power was developed as a parameter to

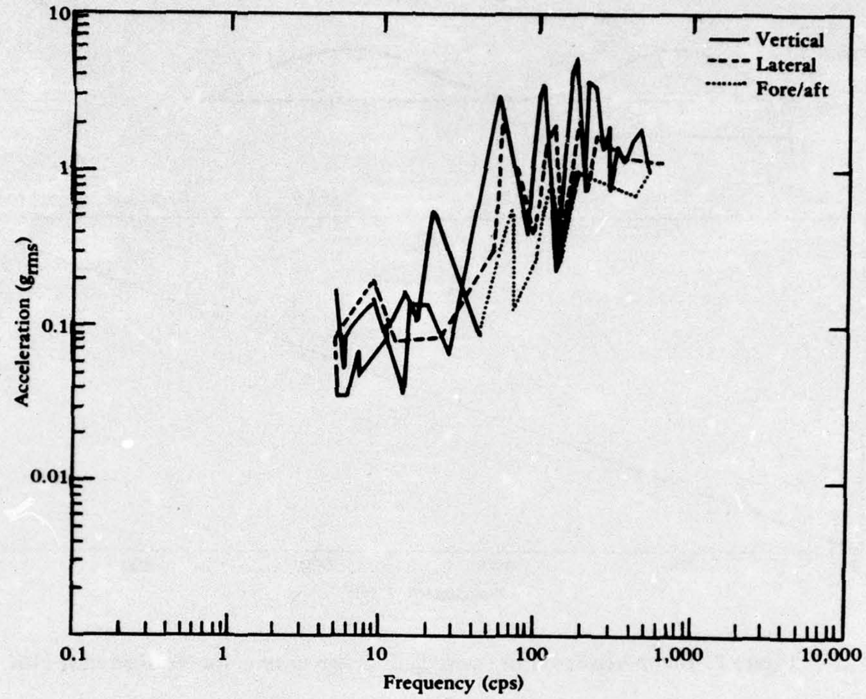

Figure 3. Acceleration envelope for C-130 aircraft [11].

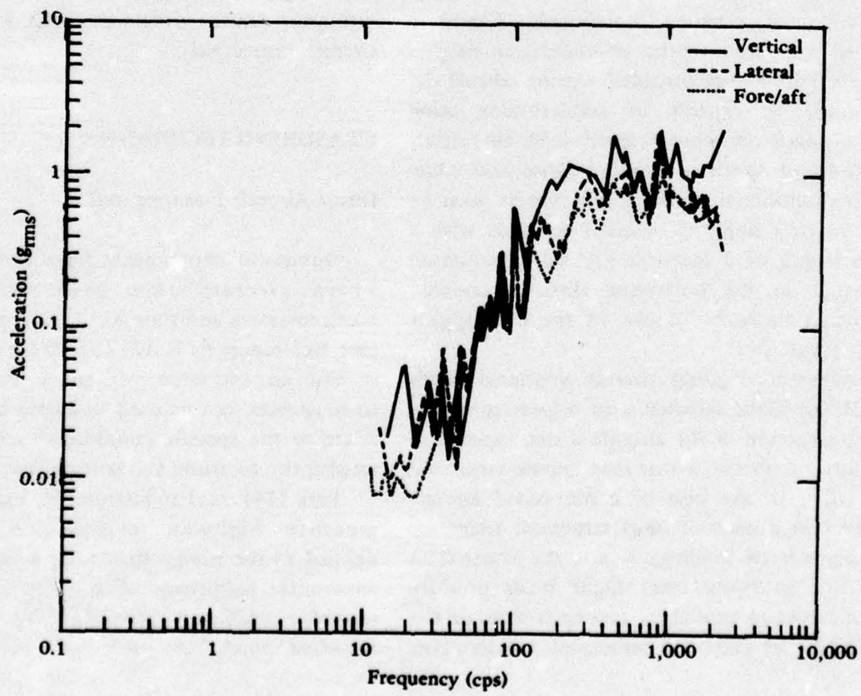

Figure 4. Acceleration envelope for KC-135 aircraft [11].

indicate roughness, but generally provides only an average value. The use of specific aircraft for determining response would be very costly as a general solution to the problem of roughness; it would be limited to the specific number of parameters considered and the types of aircraft used.

Measurement of Pavement Profiles

Since most procedures for evaluating pavement roughness start out with the pavement profile, an efficient means for determining surface profile is of major importance. Traditional procedures based upon rod-and-level survey require interruption of aircraft operations on the pavements to be surveyed. It is often not possible to close operational airfields long enough to obtain accurate surveys. Thus, to determine the runway profile, automated techniques which minimize shut-down time are desirable and would have the following characteristics:

1. Make a large number of measurements in a short time

2. Store data in an accessible manner either on magnetic tape or punch tape

3. Be rugged and transportable

4. Measure abrupt changes of the pavement surface as well as gradual changes over both large and small distances

5. Treat wavelengths from a few feet up to 500 feet (152 m) based on the resonant frequencies of the aircraft and speed of travel, with no attenuation or phase shift.

Various devices, known as profilometers, have been designed in an attempt to satisfy these requirements [15, 16, 17, 18]. Two profilometers have been evaluated at the Air Force Weapons Laboratory.

The Air Force Weapons Laboratory has developed and evaluated a surface dynamics profilometer and found it to generally meet all requirements for rapid runway profile measurements. In this device, a mass is connected to a wheel through a parallel spring-damper combination (Figure 5). The signal from an accelerometer attached to the mass is double-integrated to establish an inertial reference datum. A displacement transducer is used to measure the relative motion between the wheel, which maintains contact with the surface, and the mass. The electronically double-integrated acceleration is combined with the measured relative displacement to provide the runway profile. Additional filters may be incorporated to remove irrelevant long-wavelength components. Data can be recorded on an FM-instrumentation tape recorder and a strip-chart recorder.

In a typical runway profile survey, the vehicle is positioned at the end of the runway and the surface-following wheel lowered to the ground. A calibration consisting of a transient response and step change is performed and recorded on magnetic tape together with runway identification data and filter data, vehicle speed, and tape-recorder speed. The driver must accelerate as rapidly as possible to the predetermined constant speed and must maintain that speed throughout the run while guiding the vehicle down the set path. An analog-to-digital converter and digital computer are used to reduce data.

A laser device is also being used by the Air Force Weapons Laboratory. This device is thought to be capable of profiling a 10,000-foot (3,048-m) runway in about 2 hours [19]. It is understood that the results with the laser device are excellent, but heat waves occurring over the pavement during daylight hours made this profilometer usable only for night-time surveys. It is understood that this profilometer costs in excess of $100,000. Presumably, additional models based upon Air Force experience could be less expensive.

Measurement of Surface Variation

Many studies have been directed toward characterizing roughness in terms of deviations from some average elevation over a specific span length. Such devices are limited by their inability to identify irregularities having wavelengths exceeding the span length of the instrument. Most so-called roughometers fall within this category of devices that measure differences from some undefined mean. These devices [20] use inertial forces to maintain a relatively constant reference from which the vertical excursions of a floating wheel are measured. Roughometers generally measure such units as inches of roughness per unit length traveled, but must be correlated to recorded passenger discomfort to have any significance.

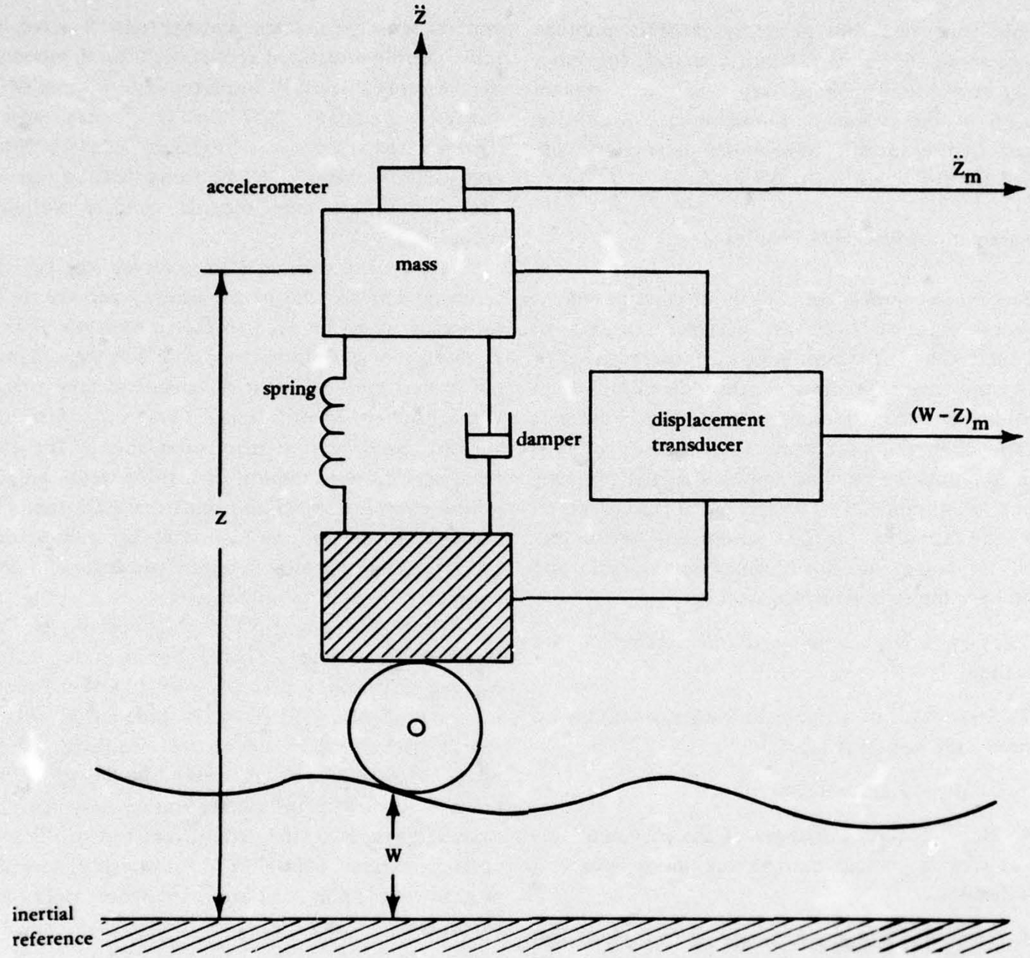

Figure 5. Profilometer sensor subsystem [18].

One such instrument, known as a Viagraphe [21], is used in France to continuously monitor the vertical displacements between a measuring wheel and the average elevation of the eight wheels of a supporting cart. The Viagraphic coefficient, defined as a function of the differences in elevations, is used to rate runways as excellent, very good, good, marginally acceptable, or unacceptable. This instrument, having an overall span length of 33 feet (10 m), was found to be relatively insensitive in predicting true aircraft response. The instrument is similar in principle to the RRL profilometer used in Britain.

Another family of techniques for measuring pavement irregularities records changes in surface slope along a horizontal path. This procedure also offers the possibility of obtaining surface profile by means of integration of the signal. However, since errors are cumulative, small errors in measurement or numerical procedures can result in large errors in the pavement profile.

ANALYTICAL TREATMENTS

Evaluation of Actual Profile

Profile data of runways can show areas of unevenness as shown in Figure 6 [22]; however,

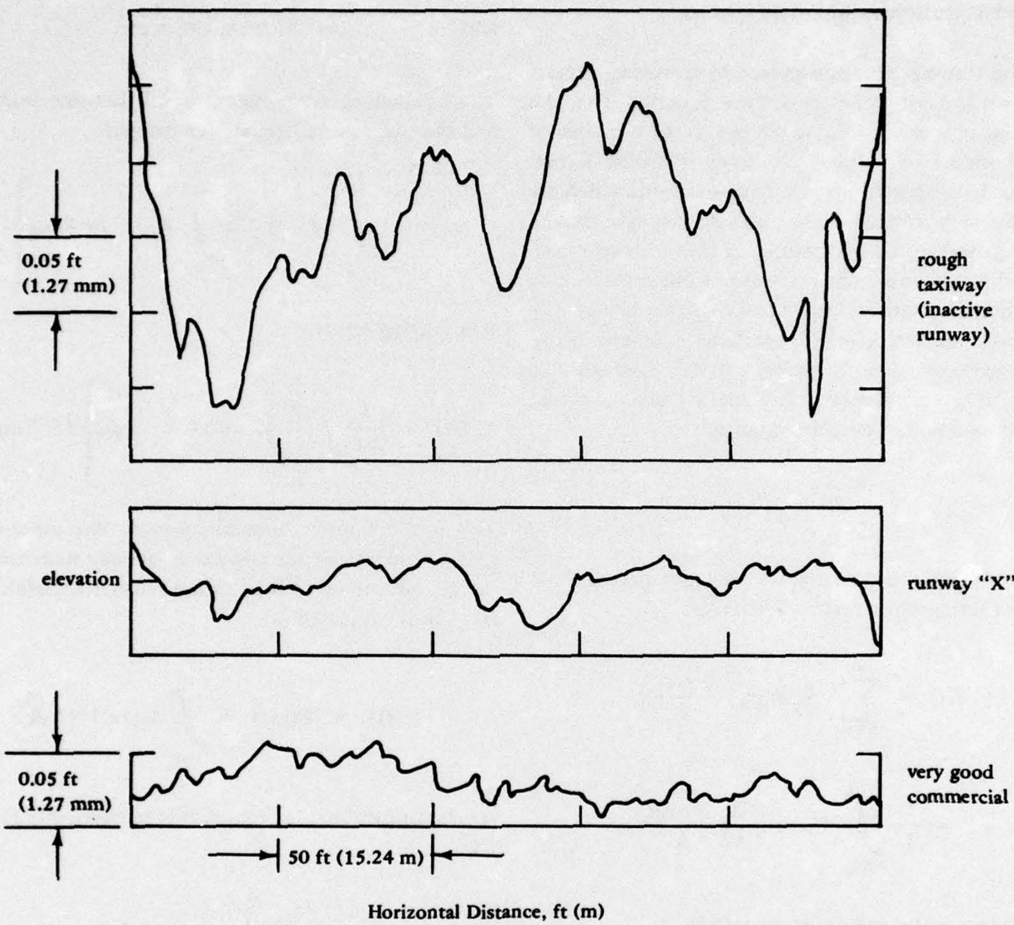

Figure 6. Representative runway elevation profiles [21].

accurate interpretation is very difficult. The runway profile is represented by a multifrequency signal with varying amplitude. An aircraft generally will respond at its own natural frequency and dampen out other frequencies. Unless it is possible to separate the various frequency components of the profile, it is difficult to determine the rough spots of the profile as they relate to a specific aircraft.

Straight-Edge Approach

In an analytical straight-edge approach [23], a hypothetical variable-length traveling straight edge is moved down a runway (that is, compared with profile data) by flipping end for end. Calculation of the deviations from the straight edge to the profile is made. The maximum deviation for each length (wavelength) of straight edge is determined over the entire runway for each starting point. The average maximum deviation for each straight-edge length is then determined. A roughness index (defined as the area under the curve of wavelength plotted against average maximum deviation) is determined. This approach lacks the capability of including the specific aircraft response and, consequently, does not really determine actual roughness. The method also does not give the location of areas in need of repair because the specific interaction among aircraft response, frequency sensitivity, and runway profile is not utilized.

Fourier Transforms and Power Spectra

The runway elevation as seen by a moving aircraft may be looked upon as a time function f(t). An inherent property of linear systems is the principle of superposition of loading functions. Periodic signals can be decomposed into a sum of sinusoids which are harmonically related, and aperiodic signals can be decomposed into a continuum of sinusoids of infinitesimal amplitudes. The response of linear systems to sinusoids is relatively easy to calculate. Use of the complex sinusoid, $e^{j\omega t}$, provides computational advantages. A time function can be expressed in terms of a continuum of elementary sinusoids and can be represented over the interval

$$-\frac{T}{2} < t < \frac{T}{2}$$

by means of a Fourier series having a period T. A Fourier series representation of f(t) is

$$f(t) = \sum_{n=-\infty}^{\infty} \alpha_n \exp\left(j\,\frac{2\pi n t}{T}\right)$$

$$\text{where } \alpha_n = \frac{1}{T}\int_{-T/2}^{T/2} f(\mu)\exp\left(-j\,\frac{2\pi n\mu}{T}\right)d\mu$$

The fundamental angular frequency is

$$\omega_o = 2\pi/T$$

In addition to being the lowest frequency component, ω_o is also the spacing between harmonics. Substituting in the above for ω_o,

$$f(t) = \sum_{n=-\infty}^{\infty} \exp\left(j\,\frac{2\pi n t}{T}\right)\left[\frac{\omega_o}{2\pi}\int_{-T/2}^{T/2} f(\mu)\exp(-jn\,\omega_o\,\mu)\,d\mu\right]$$

If T goes to infinity the spacing between harmonics will become a differential; that is

$$\omega_o = 2\frac{\pi}{T} \rightarrow d\omega \text{ as } T \rightarrow \infty$$

and

$$\omega = n\,\omega_o = \frac{2\pi n}{T}$$

The number of components n will become infinite, and the summation becomes an integral

$$f(t) = \int_{-\infty}^{\infty} e^{j\omega t}\left[\frac{d\omega}{2\pi}\int_{-\infty}^{\infty} f(\mu)\,e^{-j\omega\mu}\,d\mu\right]$$

Rearranging terms:

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} f(\mu)\,e^{-j\omega\mu}\,d\mu\right]e^{j\omega t}\,d\omega$$

This is the Fourier integral relation. The inner integral, a function of the angular frequency since time is integrated out, is defined as the Fourier transform of f(t) and is expressed as

$$F[f(t)] = F(j\omega) = \int_{-\infty}^{\infty} f(t)\,e^{-j\omega t}\,dt$$

A relationship may be established between $F(j\omega)$ and f(t)

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(j\omega)\,e^{j\omega t}\,d\omega$$

This is defined as the inverse Fourier transform of $F(j\omega)$. The term $F(j\omega)$ analyzes f(t) into a continuum of complex sinusoids having amplitudes of $1/(2\pi)F(j\omega)\,d\omega$. Such a distribution is called a frequency spectrum, and in the case of the Fourier transform $1/(2\pi)|F(j\omega)|d\omega$ can be thought of as the amplitude of the signal lying in the angular frequency band of ω to $\omega + d\omega$. The Fourier transform can be expressed more clearly in terms of the frequency spectra by

$$F(j\omega) = A(\omega)\,e^{j\theta(\omega)}$$

where $A(\omega) = |F(j\omega)|$

and $\theta(\omega) = \tan^{-1}\left[\frac{\mathrm{Im}\,F(j\omega)}{\mathrm{Re}\,F(j\omega)}\right]$

$A(\omega)$ is the amplitude spectrum or frequency spectrum and $\theta(\omega)$ is the phase spectrum.

The concept of signal spectra can be evaluated in terms of the energy as a function of frequency. The energy in a signal f(t) is given as

$$\int_{-\infty}^{\infty} [f(t)]^2\, dt$$

or

$$\int_{-\infty}^{\infty} f(t)\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} F(j\omega)\, e^{j\omega t}\, d\omega\right] dt$$

or interchanging the order and noting the definition of $F(j\omega)$

$$\text{Energy} = \frac{1}{2\pi}\int_{-\infty}^{\infty} |F(j\omega)|^2\, d\omega$$

The energy of a signal f(t) is equal to $1/(2\pi)$ times the area under the square of the magnitude of the Fourier transform of f(t). The quantity $|F(j\omega)|^2$ is called the energy spectrum of f(t) and can be interpreted as the distribution of energy with frequency.

A concept of applying runway roughness and aircraft response in terms of spectral density techniques has evolved [22]. In this concept, elevation measurements of the runway centerlines at equally spaced intervals can be used to give a "filtered" profile. Each profile contains, in a random manner, waves of different wavelengths with various amplitudes. The elevation measurements can be used to give spectra plots in which the ordinate represents the spectral density, or the relative amplitudes of roughness corresponding to specific wavelengths (see Figure 7).

This criterion evolved primarily from considerations of aircraft fatigue. Figure 8 gives a criterion for runway roughness presented in Reference 22. The spectral density gives a general measure of roughness but does not point out specific regions in need of repair. In Reference 22 it is shown that the power spectra do not give a true indication of the relative roughness of two runways since they are a measure only of the "input" and do not consider the system characteristics of the aircraft. The spectra criteria are not reliable in indicating the need for runway repair. The roughness level at which runway repairs are needed is dependent upon the response characteristics of the airplanes operated on the runway. The aircraft responds mainly to disturbances having frequencies equal to its resonance frequencies and tends to filter out all other frequencies. The energy spectra, representing an average of the roughness over the length of the runway for the various wavelengths, does not (1) distinguish between a few high amplitude bumps and the many low amplitude bumps of the same wavelength nor (2) take into account the phasing of the individual bumps. The time profile of the runway cannot be recreated since the phase-angle portion of the spectrum is not used.

Transfer Function Approach [10]

For a general linear system h(t), with input x(t) and output y(t):

$$x(t) \rightarrow \boxed{h(t)} \rightarrow y(t)$$

The relationship between input x(t) and output y(t) is given by the convolution of the input signal and the impulse response [10]

$$y(t) = \int_{-\infty}^{\infty} h(\lambda)\, x(t-\lambda)\, d\lambda$$

Taking the Fourier transform of both sides

$$Y(j\omega) = \int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} h(\lambda)\, x(t-\lambda)\, d\lambda\right] e^{-j\omega t}\, dt$$

Inverting the order of integration

$$Y(j\omega) = \int_{-\infty}^{\infty} h(\lambda)\left[\int_{-\infty}^{\infty} x(t-\lambda)\, e^{-j\omega t}\, dt\right] d\lambda$$

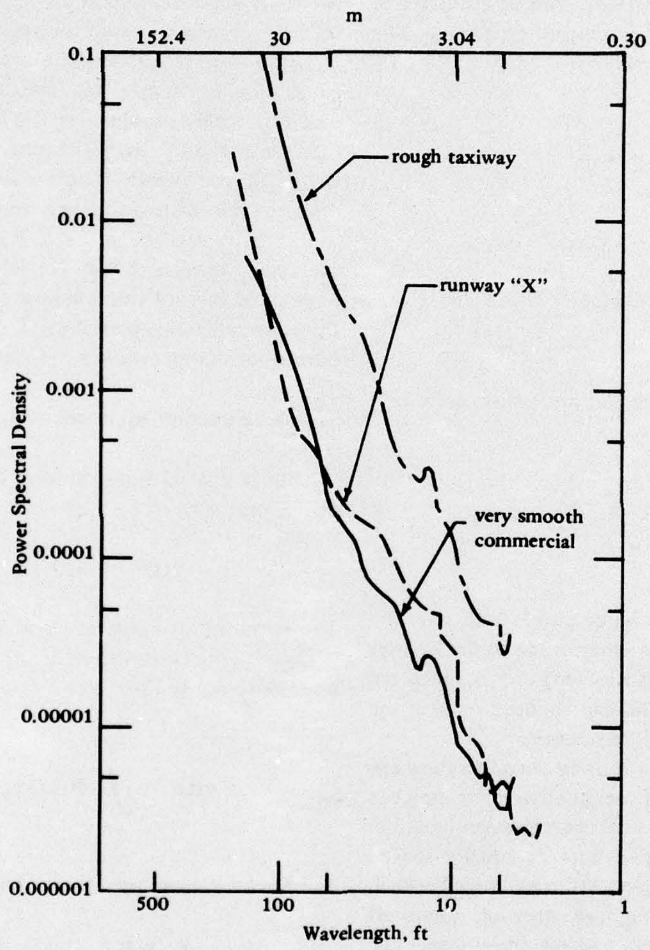

Figure 7. Typical spectra of runway roughness [21].

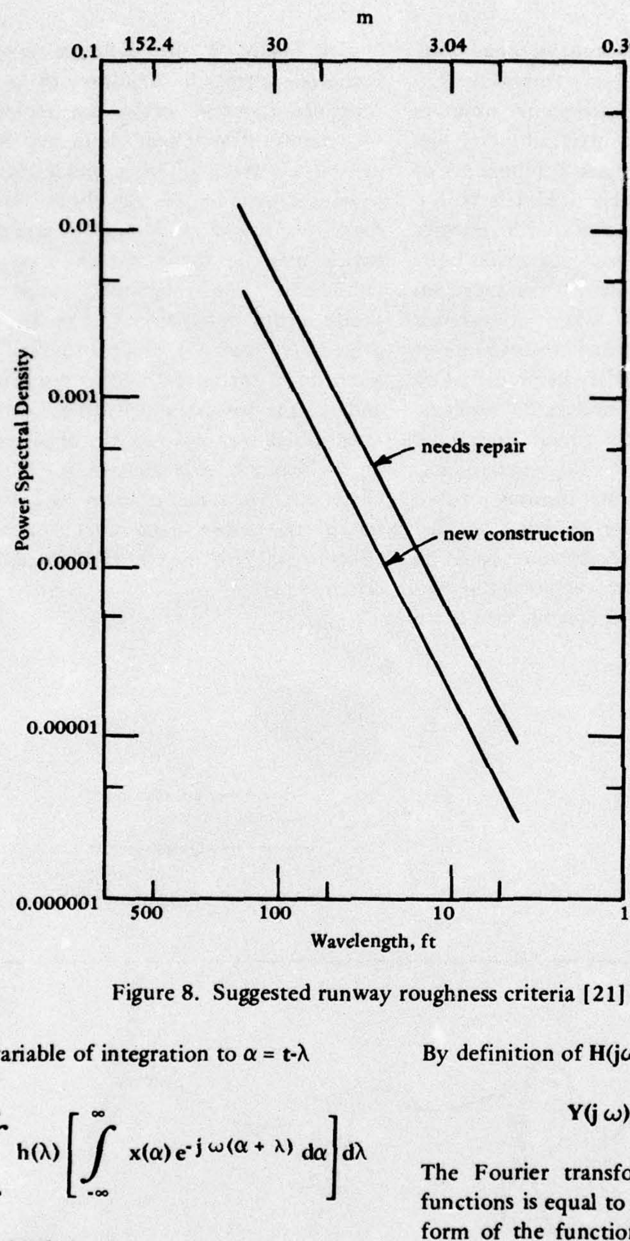

Figure 8. Suggested runway roughness criteria [21].

Changing the variable of integration to $\alpha = t\text{-}\lambda$

$$Y(j\,\omega) = \int_{-\infty}^{\infty} h(\lambda) \left[\int_{-\infty}^{\infty} x(\alpha)\, e^{-j\,\omega(\alpha + \lambda)}\, d\alpha \right] d\lambda$$

By definition of $X(j\omega)$

$$Y(j\,\omega) = \int_{-\infty}^{\infty} h(\lambda)\, e^{-j\,\omega\,\lambda}\, X(j\,\omega)\, d\lambda$$

$$= X(j\,\omega) \int_{-\infty}^{\infty} h(\lambda)\, e^{-j\,\omega\,\lambda}\, d\lambda$$

By definition of $H(j\omega)$

$$Y(j\,\omega) = X(j\,\omega)\, H(j\,\omega)$$

The Fourier transform of the convolution of two functions is equal to the product of the Fourier transform of the functions taken separately. The Fourier transform of the output of a linear system is given by the Fourier transform of the input $X(j\omega)$ multiplied by the Fourier transform of the system impulse $H(j\omega)$. The system function

$$H(j\,\omega) = \frac{Y(j\,\omega)}{X(j\,\omega)}$$

is the transfer function relating output to input (note that $H(j\omega)$ is complex having both amplitude and phase angle). In a given linear experimental situation where it is possible to measure $x(t)$ and $y(t)$ and compute both amplitude and phase components of $X(j\omega)$ and $Y(j\omega)$, then it is possible to specify $H(j\omega)$.

A simplified approach utilizing linear transfer theory will now be discussed. Assume a transfer function for a specific aircraft is known. If the spectrum of elevation values of the airfield is known, as shown in Figure 7, the power spectrum of the response of the specific aircraft to the airfield can be predicted by direct multiplication. The area under the resulting power spectrum then indicates aircraft response. Thus, having the transfer function for a specific aircraft, one could input a particular runway profile characterization and calculate aircraft response. This approach, although theoretically reasonable, could be expected to be relatively complex when realistic nonlinear transfer functions and airfield profile inputs are used.

In Figure 9 the ordinate represents cockpit vertical-acceleration response to a periodic unit-roughness input at various frequencies for three types of aircraft. The lowest frequency in each wave is caused by the rigid-body pitch mode; the highest peak is caused by the rigid-body vertical-translation mode. Additional modes from structural responses, which may be significant in many cases, are not considered. The roughness wavelengths that will produce the most aircraft response are dependent primarily upon: (1) the predominant response frequencies of the aircraft, (2) the speed of the aircraft, and (3) the weight and stiffness of the aircraft. The range of runway wavelengths of interest is dependent on the response characteristics of the particular type of aircraft. The sampling rates used in computation of the spectral density must reflect this, and wavelengths of up to 500 feet must be considered in the roughness criteria [11].

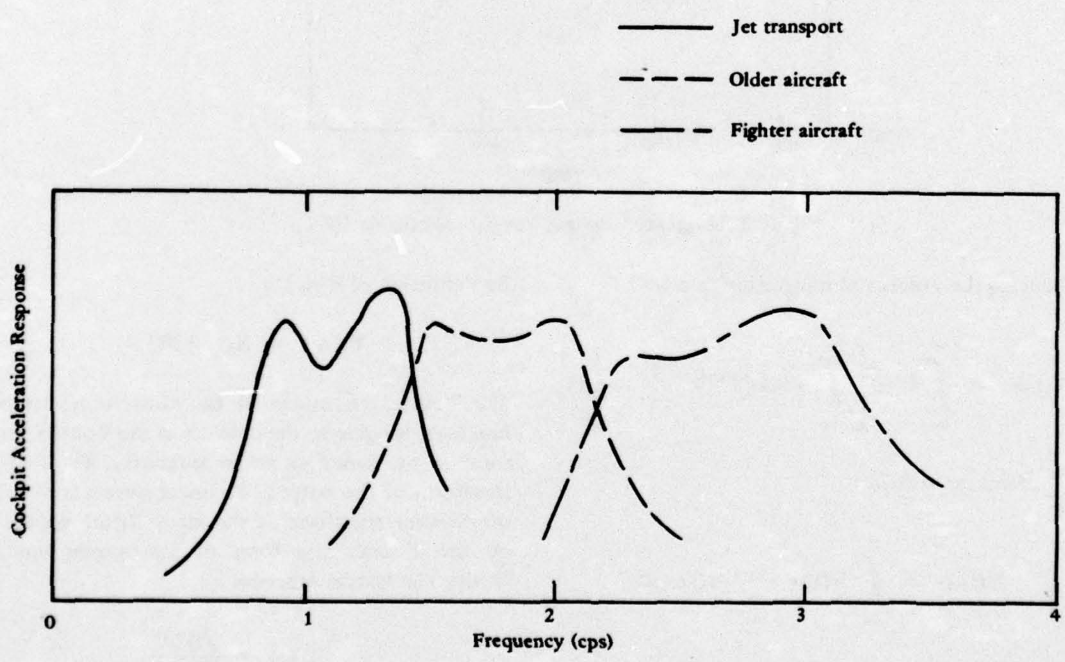

Figure 9. Comparison of frequency-response functions for present-day and older aircraft types [21].

Automated Simulation Techniques

Computer programs have been developed which provide aircraft response as a function of such variables as position on the pavement and speed of travel. Coupling occurs between airplane response and pavement profile in that the aircraft causes transient deflections to the pavement as it is loaded; such deflections, in turn, change the profile. Current approaches to aircraft response predictions generally ignore the aircraft-induced changes in pavement elevation and assume an invariable surface profile. Both analog and digital computer models have been used to simulate aircraft/pavement interaction.

NASA used profile data converted to voltages to drive an analog model of a simplified aircraft [24]. Simulated repairs were evaluated. Such simplified models as this serve to illustrate the complex interdependencies of the various aspects of aircraft response. For example, an analysis considering only rigid-body modes of response showed calculated accelerations that were lower than an analysis in which flexible aircraft modes were considered.

A similar digital-computer model was developed [25] and improved [26] using the power spectral approach. A code developed by Boeing [27] having many degrees of freedom was used in roughness studies, but this program was very expensive to use. A later code by Lockheed-Georgia [28] was somewhat less prodigious, but still relatively expensive to use.

Among the various computer programs reviewed [8 and 24 through 29], the program described in References 29 and 8 developed at the Air Force Flight Dynamics Laboratory appeared to be most applicable to roughness evaluations. This program has undergone extensive verification with measured aircraft responses. Also, though some of the earlier aircraft response models were developed to simulate aircraft response to all types of excitation, this code is designed specifically to consider pavement roughness only. Therefore, this code is simple to use and requires a minimum of computer time.

A digitized pavement profile is input to a general model of a flexible aircraft with landing gear, struts, and tires. The model includes pitch, vertical translation, horizontal translation, and up to 15 flexible modes of vibration. The detailed model incorporates a flexible fuselage with one nose gear and multiple main landing gear. The landing gear struts can be conventional, articulated, or double acting. The model includes lift, thrust, and aerodynamic and rolling drag. The individual runway profile points are curve-fitted to a polynomial equation using the slope and three elevation points to solve for the required coefficients. The slope at the beginning of a runway segment is made to equal the slope at the end of the previous segment. A 2-foot (0.6 m) interval between points is used. The technique used to solve the coupled nonlinear differential equations of motion utilizes a three-term Taylor Series approximation for displacement, using acceleration, velocity, and displacement from a previous step. The program produces a plot of the vertical-acceleration with distance down the runway. This plot shows runway locations producing high accelerations. Figure 10 is a sample plot, showing computer data and experimentally recorded results.

Figure 11 shows a portion of a runway producing an acceleration peak of about 1.0 g in a C-9 aircraft traveling at 100 ft/sec (30 m/sec). The distance from nose gear to main gear of 80 feet (24.4 m) indicates the most sensitive resonant wavelength would be about 160 feet (48.8 m) (twice the distance between gears). In this case a bump with an approximate wavelength of 160 feet (48.8 m) and a peak-to-peak amplitude of 1 inch (2.54 cm) was thought to be the cause of the 1.0-g response. Figure 12 shows a simulated repair eliminating the bump and, as a result, eliminating the high acceleration.

DISCUSSION

Mechanism of Roughness

One may think of a runway profile as a forcing function transmitting random vibration into an aircraft. This random vibration can be a composite of all frequencies. However, those frequencies to which aircraft will respond generally fall within a narrow band of less than 15 cycles per second. The lower frequencies, particularly with stiffer fighter aircraft, are associated with the rigid-body modes of response. These frequencies are very largely controlled by the characteristics of the landing gear. Vertical

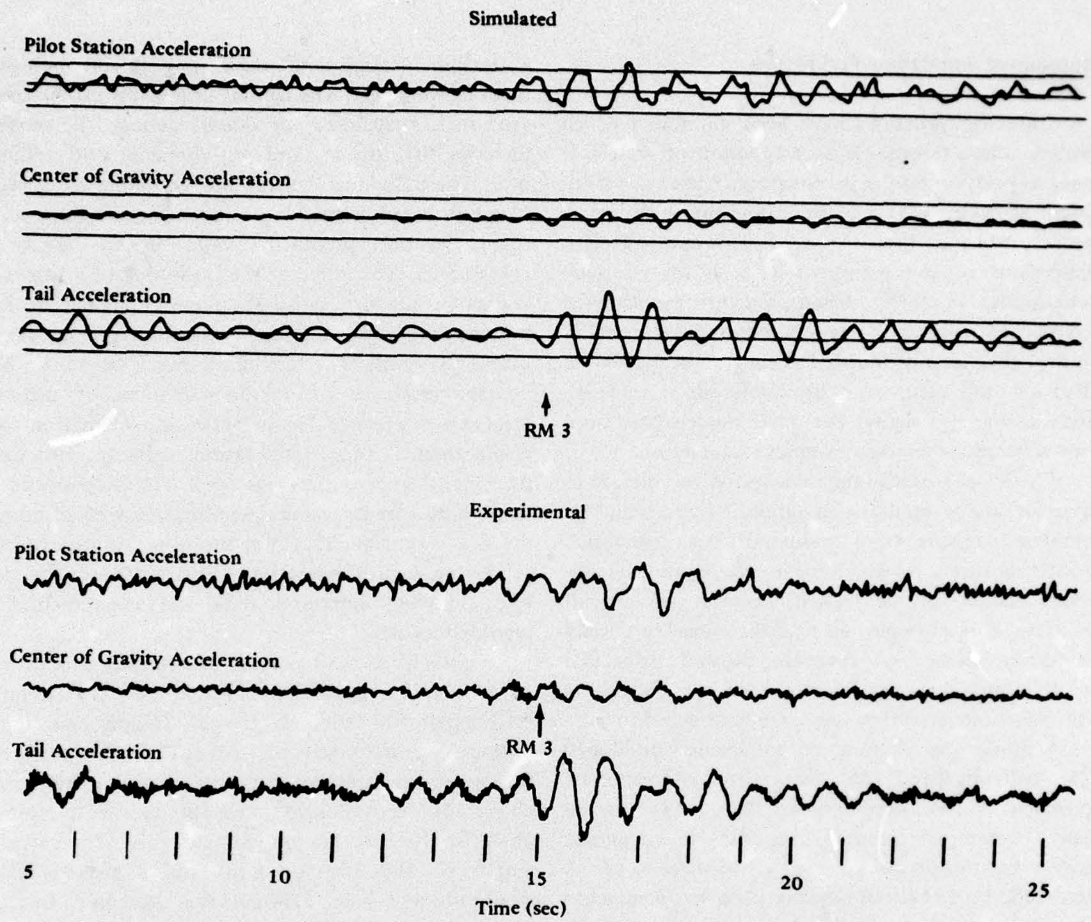

Figure 10. Comparison of computer-simulated and measured acceleration time histories of test aircraft during a 40-knot taxi.

translation, or plunging, generally takes place at about 1 to 2 cycles per second, while pitching may fall within the 2- to 3-cycle range. With large transports these frequencies will be somewhat lower. Higher modes include the fuselage flexibility mode. However, with very large aircraft, this mode can be in the same frequency range as the rigid-body modes. The flexibility of the wings is significant, particularly where wing-tip fuel tanks or other wing loads are attached. Placing tanks on the wings decreases the flight loads on the wings but increases the stresses on the wings during taxiing.

The number of modes to be considered in predicting aircraft response should include at least those frequencies for which the energy flow is high enough to perceptibly influence aircraft performance. This generally lies somewhere between 8 to 15 modes, with the frequency range of interest below about 13 cycles per second. For example, frequency content determinations on a KC-135 aircraft [4] show predominant frequencies of 0.8, 3.6, and 6.6 cycles per second. Such information indicates that the critical wavelength for rigid-body modes of oscillation are about twice the distance between the main and nose landing gears. Because an interaction between aircraft response and pavement profile exists, it is not sufficient to determine the overall pavement characteristics, as in the spectral-analysis approach, or to consider individual departures from a datum, such as height of bump over a prescribed distance. The sequences of irregularities must also be considered, since reinforcing and interfering of different frequency components occur. This type of behavior also makes it difficult to ascertain with precision the specific anomaly causing an undesirable response level.

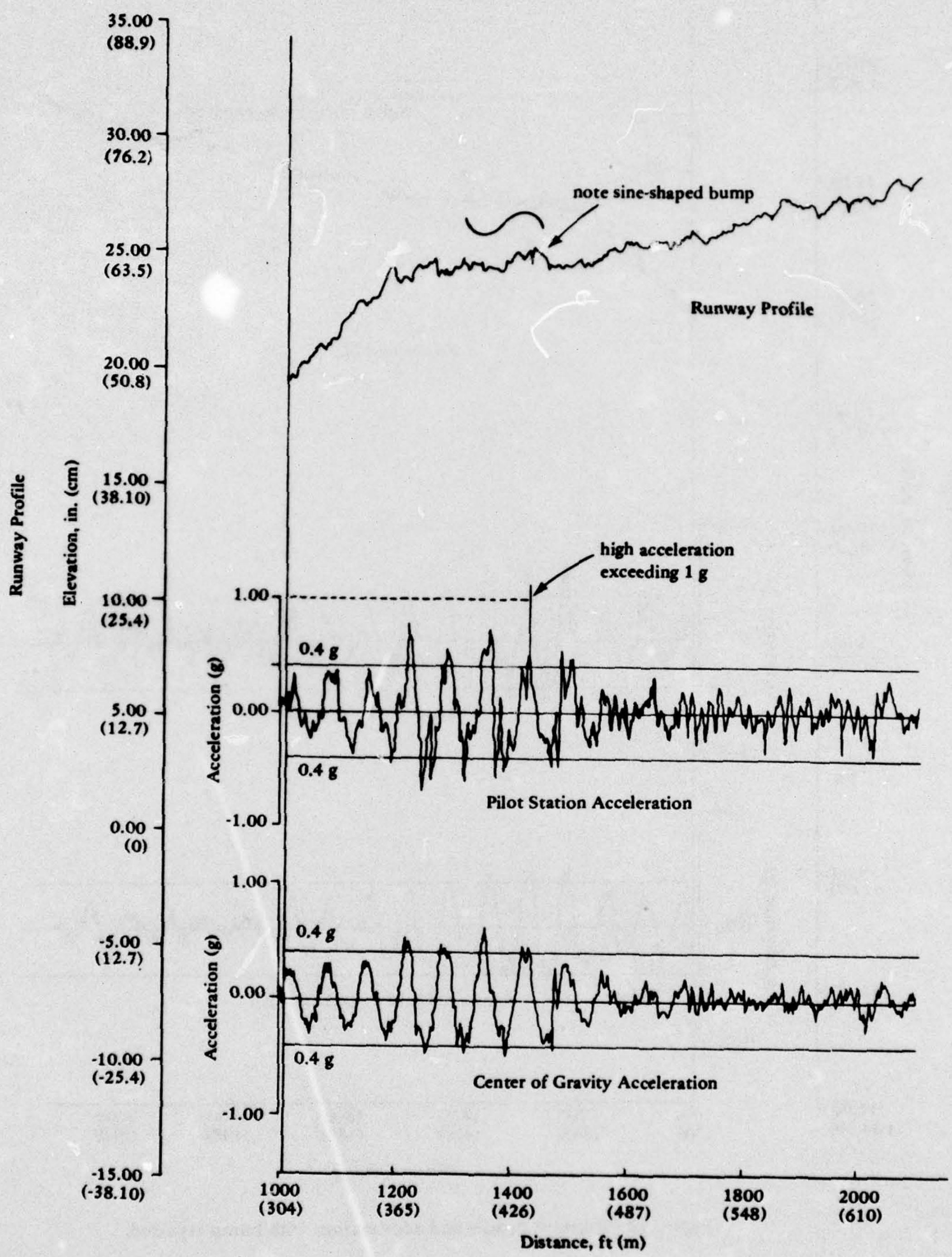

Figure 11. Runway profile and acceleration of a C-9 aircraft.

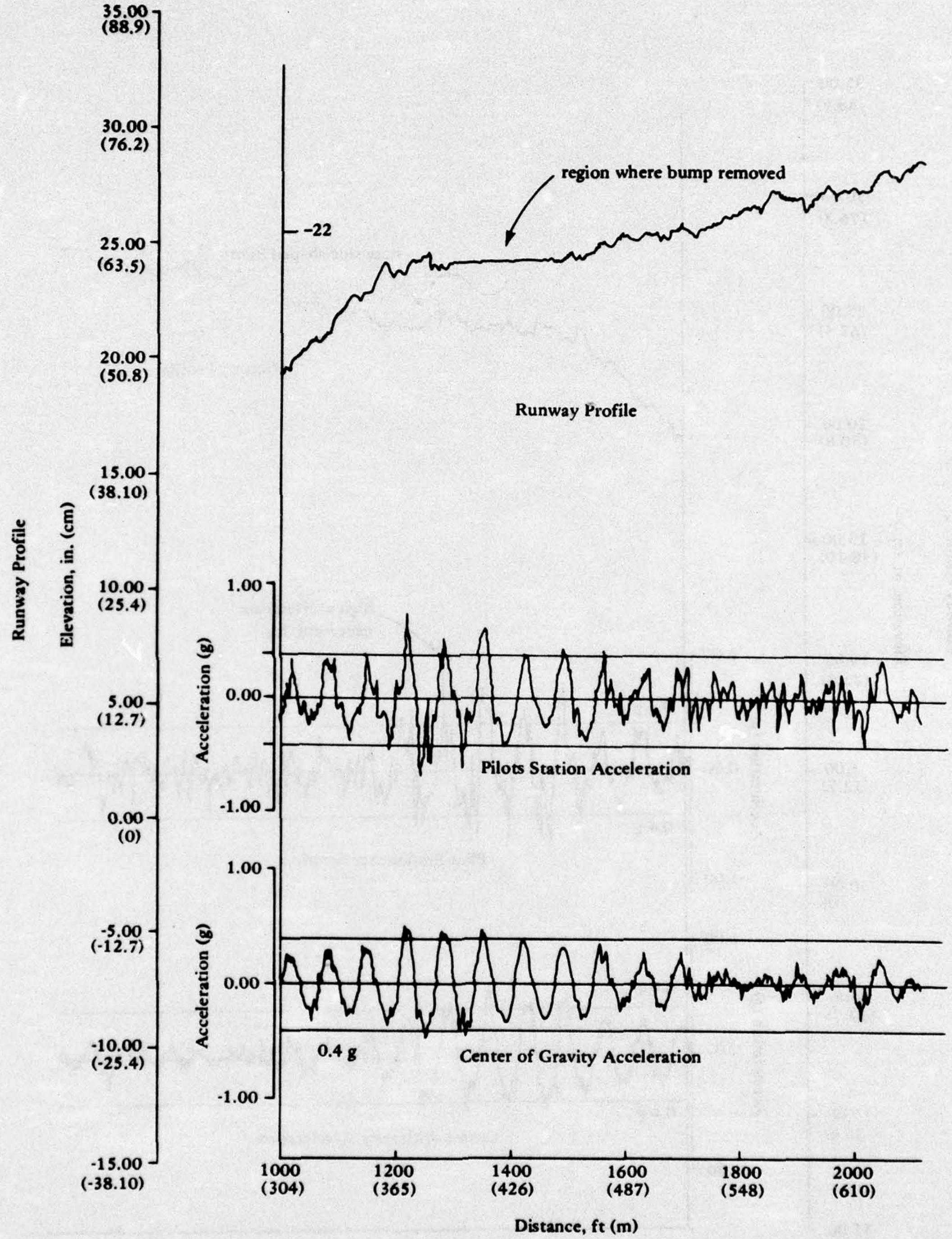

Figure 12. Runway profile and acceleration with bump repaired.

Significance of Roughness to the Navy

Rough pavements do not appear to be a widespread problem for Naval air operations. Pilot complaints are generally handled satisfactorily by Public Works Departments. Generally, any unusually bad areas are obvious to the Public Works Departments and are fixed accordingly. Roughness during a particular air operation may occur on a section of pavement which may not be evident to the Public Works repair crews conducting visual inspections of pavements. This is particularly true for taxiways.

A random telephone survey of 25 Naval Air Stations was made through the Air Operations Officer, who in most cases was a pilot. Questions were asked about the type of aircraft operating on the field, the condition of the runways and taxiways, and pilot complaints. The conclusion of the survey is that the Navy does not have a widespread problem of runway roughness. There were, however, several specific locations which were noted as having roughness problems. These are discussed below.

1. NAS Norfolk VA. A section of runway 10-28 between about the 3,000-to 7,000-foot (914 to 2,133 m) markings is rough: C-9 aircraft cannot go into full engine reverse. Nose-wheel shimmy is noted. The problem is generally noted in landings; during takeoff aircraft are generally airborne before passing the region.

2. NAS Patuxent River MD. A portion of taxiway E is rough for P-3 aircraft.

3. NAS Cecil Field FL. The runway is considered rougher than average.

4. NAS Point Mugu CA. The runway and taxiway E are rough in spots, causing vibration in the nose wheel of F4 aircraft.

5. NAFEC Atlantic City NJ. This airfield has a rough taxiway. Also, taxi speeds of aircraft, such as the P-3 with wing-tip tanks, must be drastically reduced on most taxiways to prevent leaking of the tanks.

Each of these cases can be analyzed using the computer code recommended in this report. A survey to determine profile elevations at 2-foot (0.6 m) intervals would be required. This appears to be the most direct and cost-effective method for locating rough spots and determining the extent of necessary repairs.

SUMMARY AND CONCLUSIONS

The problem of airfield pavement roughness was investigated to determine two things: (1) if roughness affects Naval air operations, and (2) the procedures that should be adopted if it is necessary to incorporate evaluation of roughness into regular Navy airfield pavement-evaluation procedures.

It was apparent that except for a very few specific cases, roughness of airfield pavements is currently handled satisfactorily with normal pavement repair procedures. For the few exceptions noted, where special consideration is necessary, an analysis using a computer-code simulation of aircraft response is recommended. A computer code, developed by the Air Force Flight Dynamics Laboratory and deemed to be most applicable to Navy problems, has been obtained and is operational at CEL. This approach requires determination of runway profiles, either by standard rod and level survey or by one of the new profilometer devices being used by the Air Force Weapons Laboratory. There is a need to standardize the criteria used to define unacceptable levels of roughness. The standard that is most acceptable appears to limit vertical acceleration to 0.4 g.

The computer-code analysis of pavement roughness can be used to evaluate proposed pavement repairs and is more efficient than all other procedures reviewed.

RECOMMENDATIONS

The following recommendations are made.

1. When construction of all new airfield pavements is completed, pavement profiles at 6-inch (15.2 cm) intervals should be determined. This will allow monitoring the performance of the pavement and will enable engineers at a future time to determine changes in profile and roughness during the service life of the pavement. This data should be compiled into a library readily adaptable to ADP procedures. CEL could provide guidance in establishment of such a data bank.

2. Construction techniques such as slipforming should be reviewed to establish required standards for vertical control of the pavement surface to eliminate roughness in new construction.

3. Any major repairs thought to be necessary because of roughness should be evaluated by use of the presently available computer code.

4. Since the roughness problem does not appear to be widespread in the Navy and since a survey to determine the centerline profiles of a runway would necessitate ceasing airfield operations, a roughness evaluation should not be included in airfield-condition surveys at this time. Pilot comments can be used as indicators of problem areas requiring more detailed investigation. Direct personal contact should be maintained between Public Works personnel and Air Operations Officers at each station to insure that pilot comments are noted and that, when complaints develop, specific sections of pavement can be evaluated to determine if aircraft accelerations exceed 0.4 g.

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